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DATA COLLECTION, INSTRUMENTATION AND VERIFICATION OF MODELS

by

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Abstract

Data requirements for computer modelling of urban runoff are discussed. Two types of data are generally required, input data and calibration/verification data. The input data consist of hydrometeorologic, process, physical, and environmental quality parameters. Methods and means of obtaining such data are discussed.

The calibration/verification data consist of synchronized observations of rainfall, runoff hydrographs, and runoff pollutographs. The required accuracy of such data, and the required number and type of calibration/verification events are briefly examined. The collection of calibration/verification data is described as a hydrological network problem.

Finally, an overview of instrumentation for urban runoff studies is given. In particular, rain gauges, flow gauges, wastewater samplers, and recorders are discussed. Recommendations are offered for the selection of instruments as well as for the operation of data collection programs.

<u>Collecte de données, choix d'instruments et vérification de modèles</u>

J. Marsalek

RESUME

L'auteur étudie les exigences en matière de données pour l'établissement de modèles informatiques de l'écoulement urbain. Deux types de données sont généralement nécessaires, les données d'entrée et les données d'étalonnage et de vérification. Les données d'entrée consistent en paramètres d'hydrométéorologie, de processus, de physique et de qualité de l'environnement. Les méthodes et les moyens d'obtenir de telles données sont étudiés.

Les données d'étalonnage et de vérification consistent en observations synchronisées des précipitations, en hydrogrammes d'écoulement et en pollutogrammes d'écoulement. La précision requise dans le cas de telles données ainsi qui le nombre et le type de cas d'étalonnage et de vérification sont examinés brièvement. La collecte de données d'étalonnage et de vérification est décrite comme un problème de réseau hydrologique.

Enfin, l'auteur donne une vue d'ensemble des instruments utilisés pour les études de l'écoulement urbain. Il étudie en particulier les pluviomètres, les débitmètres, les échantillonneurs d'eaux résiduaires et les enregistreurs. Il fait également des recommandations en matière de choix d'instruments et d'exploitation de programmes de collecte de données.

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DATA COLLECTION, INSTRUMENTATION AND VERIFICATION OF MODELS

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1. Introduction

The planning and design of water resources development cannot be successfully conducted without the availability of a wide variety of basic data relating to the locality of the actual engineering works as well as to the entire region that will benefit or be affected by the project. Such a need for data is particularly strong in the development of urban water resources. The discussion concentrates on a particular field of urban water resources, urban drainage.

While the conventional design of urban drainage was limited to removal of surface runoff to a convenient water course, modern drainage provides for a balanced combination of natural and man-made drainage elements which are designed not only to provide an adequate flood protection for urban developments, but also to minimize the drainage impact on receiving waters. Such increasing sophistication of drainage design requires application of sophisticated design tools and the availability of a variety of supporting data.

A recent conference on urban runoff concluded [1] that though there has been progress made in the acquisition of urban field data, the needs for more and better data are growing faster than such advances taking place.

When speaking of urban drainage data, it should be realized that such data can be produced in a variety of ways. The most reliable estimates of runoff flow rates and pollutant concentrations are field data obtained from extensive local monitoring programs. Since it is impractical to obtain such data at every point of interest, and time and budget constraints as well as physical changes in the area sometimes prevent such monitoring programs, other methods may have to be used to provide the data required. Among these methods, hydrologic modelling appears to be the best alternative . Various types of data required for the application of urban runoff models and means of collecting such data are discussed in the following.

2. Data Requirements for Modelling of Urban Runoff

Two types of data are required: Firstly, input data, and secondly, calibration and verification data. The requirements on such data vary depending on the purpose of the study and the modelling tool used. Consequently, only a general discussion of such requirements, with a special reference to the SWMM and STORM models, is given here.

2.1 Input Data for Urban Hydrological Modelling

Data for deterministic hydrological modelling can be classified [2] into three groups:

(a) Hydrometeorologic parameters
(b) Process parameters
(c) Physical parameters

In the case of models dealing also with the water quality aspects, another category is added:

(d) Environmental quality parameters.

2.1.1 Hydrometeorologic parameters

Depending on the type of model used, hydrometeorologic parameters may include precipitation, evaporation, flows, and for snowmelt computations, also temperature, snow depth, wind and sunshine or solar radiation. Only the most important parameter - precipitation is discussed here; for other parameters, the reader is referred to ref. [3].

Precipitation is the most important input to a simulation model of the land phase of the hydrologic cycle.

In urban hydrology, the rain form of precipitation is particularly important. The requirements on rainfall data are rather stringent. Rainfall data, typically recorded in the increments of 0.01 inch (0.25 mm) must be available at short intervals. In most design cases, such interval varies from 5 to 15 minutes. For planning purposes, hourly rainfall data may be acceptable. Table 1 [4] offers general guidelines for the selection time intervals depending on the size of the catchment and study objectives.

Since the precipitation depth reduces somewhat with an increasing catchment area, more than one rainfall record may be required for catchments with areas larger than one square mile.

The best source of long-term rainfall data in Canada is the Atmospheric Environment Service (AES). Data can be obtained from the AES either on magnetic tape files (hourly data), or through actual daily records on stripcharts.

2.1.2 Hydrologic Process Parameters

In deterministic hydrology, it is assumed that the relationships between the many interacting factors affecting the water balance can be defined analytically. The numeric values used to quantify the

TABLE 1. RECOMMENDED TIME RESOLUTIONS OF PRECIPITATION DATA FOR URBAN RUNOFF STUDIES [4]

Watershed Type	Size		Time resolution
	Acres	Hectares	minutes
Small Experimental Watersheds (for model development or calibration)	10 - 300	4 - 120	1 - 2
Large Experimental Watersheds	500 - 3000	200 - 1200	5
Data Serving for Design	up to 3000 >3000	up to 1200 >1200	5 - 10 10 - 15
Data Serving for Planning	>3000	>1200	60

factors affecting the distribution and movement of water are termed parameters. The parameters which quantify the movement and storage of water in and on the land surface of a catchment are called process parameters and are the key to catchment response. They include infiltration, surface and lower zones storage, interception, overland flow parameters, runoff coefficients, interflow, transpiration, snowmelt parameters and others. Only some of these parameters are important in urban hydrology, namely, infiltration, surface storage, overland flow parameters and runoff coefficients.

Although some process parameters can be measured directly, in some cases this may be difficult or impractical and the numerical values of these parameters are obtained either by calibration or transposition from other similar catchments.

<u>Infiltration</u>. The importance of infiltration in urban catchment hydrology depends on the catchment imperviousness. In downtown areas with high imperviousness (80% or more), pervious areas contribute very little to the total runoff and an accurate estimate of infiltration is of little importance. On the other hand, the pervious surface may contribute significantly to the total runoff from partly developed (low imperviousness) areas and a good estimate of infiltration is needed.

Best estimates of infiltration rates are obtained by calibration of simulated runoff hydrographs against the observed ones [5]. The variation of the infiltration rate, i[inch/hr], during a storm is frequently described by the Horton formula:

$$i = f_o + (f_i - f_o)\, e^{-ct}$$

where f_o = minimum infiltration rate [inches/hour]

f_i = maximum infiltation rate [inches/hour]

c = decay rate [1/sec]

t = time from the start of rainfall [sec].

The Horton formula contains three coefficients f_o, f_i, and c, which can be easily calibrated. This contributes to the widespread use of the formula in urban hydrology, even though more advanced approaches to infiltration have been developed [6]. For numerical values of the above noted coefficients, references [7, 8] should be consulted.

On impervious areas, zero infiltration is typically assumed.

Surface Storage. The surface storage consists of the depression storage and storage on the overland flow plane. The former storage is typically assigned a constant value, the latter storage varies during the computations. Basically, the surface storage creates a time lag between the surface element inflow (i.e. rainfall) and outflow (runoff).

Depressions on natural surfaces vary greatly in geometry. The depth of depression storage may be determined by calibration, or by transposition of data from other urban catchments. Some guidance can be obtained from the data in Table 2.

	Surface Depression Storage [inch]	
	Impervious	Pervious
SWMM Default Value	0.062	0.184
Calibration values	0.02[9], 0.04[10]	0.10 [11]

Table 2. Surface Depression Storage on Urban Catchments

Overland flow parameters. Examples of such parameters are the overland flow roughness and the width of overland flow plane (under some circumstances, this is a physical parameter). The roughness is usually described by the Manning coefficient n. The values of n = 0.013 and n = 0.25 are recommended [8] for impervious and pervious areas, respectively.

The width of the overland flow plane as used e.g. in the SWMM model may become a process parameter. Though this width is related to the physical width of the catchment it may assume a function of a process parameter derived from calibration [12]. This is particularly true for coarsely discretized catchments. The width of the flow plane may then deviate significantly from the actual width in order to simulate properly the catchment response.

Runoff Coefficient. In simple runoff computations, the runoff coefficient can be used as a crude index which combines some or all factors affecting runoff. Such an approach is for example taken in the STORM model [13]. Numerical values of runoff coefficient are listed in design manuals [14,15].

2.1.3 Physical Parameters

The definition of physical parameters of a catchment and of its subcatchments is a relatively straight forward task. The detail of such data depends on the level of modelling, and under some circumstances, the collection of physical parameter data is a tedious task contributing significantly to the total cost of modelling.

At the planning level, a very rough characterization of the catchment may be acceptable. In fact, the details of the sewer system may be disregarded at this level. At the design level, however, more detailed information is gathered from aerial photos, drainage maps, sewer plans, topographic maps, soil maps, etc. Below are listed the types of information which may be of interest in detailed modelling of quantity and quality of urban runoff [16].

The catchment should be characterized as to area; impervious area; effective impervious area (directly connected impervious area); pervious area; contributing pervious area (pervious area that would, if subjected to heavy rainfall, contribute runoff to the drainage system); street lengths, widths, slopes, surface type, and condition; soil types; length of curbed streets versus non-curbed streets; land-use distribution; location and size of catchbasins; inlet-characteristics; ground-surface elevations at pipe junctions; conduit invert elevations and material types; conduit and open-channel length, slopes, sizes, geometry and friction factors; and pertinent characteristics of special drainage features such as detention basins, and any other features special to the catchment of interest.

2.1.4 Environmental Quality Data

Investigations of runoff quality require supporting data referring to sources of pollutants and measures for control of pollutants. Though some of these data could fit into the previously specified categories, it appears preferable to treat the environmental quality data separately. Note also that this type of data is needed only in the water-quality oriented studies of drainage.

Sources of Pollution and their quantification.

Pollutant loads are introduced into storm water and combined sewage from the following sources:

(a) Rain water contamination
(b) Land surface
(c) Soil erosion
(d) Dry weather flow
(e) Deposits in sewers and catchbasins.

The contamination of rain water is typically neglected in water quality studies of urban runoff.

The accumulation of pollutants on the land surface represents an important source of pollution. Pollutants accumulate during the periods of dry weather and are washed off during storms. Such accumulations can be computed, for a particular area, by multiplying the dry weather period in days by the daily loading rates. Such loading rates vary with the type of pollutant and with the land use. Reference [13] is a good source of loading rates.

Urban soil erosion may contribute significantly to the total emission of solids from the catchment, particularly in the case of catchments with ongoing construction activities. The resulting soil loss per unit area is described by the Universal Soil Loss Equation [17]. This equation was used recently to predict the average soil loss for a given storm or time period and for details the reader is referred to reference [18].

Dry weather flow is another major source of pollutants included in the modelling of water quality of combined sewage. Flow records and composition data are available in many locations and can be readily used in computations. If such data are not available, a number of references can be consulted [8,14].

The mechanism of deposition and resuspension of pollutants in sewers may significantly affect the composition of sewage, particularly in combined sewers with flat slopes. Such mechanism is not well understood at present and is quantified indirectly through model calibration [8].

The contribution of catchbasins to the total emission of pollutants is usually of secondary importance [18].

<u>Pollution control measures.</u>

Street sweeping and various forms of treatment are common methods of control of pollution due to urban drainage. Pollutants accumulated on the catchment surface are partly removed by sweeping streets. This pollutant removal can be quantified if the frequency and efficiency of sweeping streets are known [8].

Various methods of treatment of storm water and combined sewage have been developed [18]. Such methods range from primary clarification to combinations of several treatment processes. For details of such treatment processes, see ref. [8].

2.1.5 Cost Data

Proper design of urban drainage minimizes the cost of flood damages due to underdesign and economic inefficiency due to overdesign [3]. Such design can be arrived at by developing the cost-benefit relations in which the cost is the drainage construction costs and the benefits are the prevented flood damages. The latter data, flood damages, are rather scarce and that prevents a wider use of the cost-benefit analysis in urban drainage design.

Water quality benefits can be hardly expressed in dollars as required in the cost-benefit analysis. As an alternative, water quality objectives are specified and a design scheme meeting these objectives at a minimum cost is sought. Such a procedure requires the knowledge of the cost of various quality control measures. For a first-cut analysis, such costs can be obtained from references [8,12].

2.1.6 Input data for the SWMM and STORM models

For a better appreciation of requirements on input data in urban hydrologic modelling, input data for two selected models, the SWMM and STORM, are listed in Table 3.

Note that all the data listed in Table 3 are needed only in those cases when the entire model is applied. Some of the data listed can be transposed from other catchments or be supplied by the model as default values. Only in detailed and complex design simulations one needs to deal, to a various extent, with all the types of input data listed in Table 3. The selection of an appropriate detail of the input data can be aided by model sensitivity analyses [12].

2.2.1 Calibration and verification of models

The calibration of a runoff model is a procedure in which model parameters are manipulated to reproduce the response of the catchment under study within some range of accuracy. Calibration is not a problem unique to hydrologic simulation. Any hydrologic procedure will yield better results if tested against observed data and any constants are appropriately fixed by data from the area studied.

Main advantages of calibration are as follows:

(a) Calibration produces estimates of input parameters that are difficult to measure directly (e.g. infiltration rates, pollutant loadings)
(b) Calibration compensates, to some extent, for imperfections or omissions in the model structure
(c) Calibration together with verification lend reliability to the model predictions.

Once a model has been calibrated against a set of calibration

SWMM Model	STORM model
Rainfall data, antecedent dry days	Hourly rainfall
Subcatchment descriptions including area, overland flow width, slope, roughness coefficients, infiltration rates, percent imperviousness	Area of drainage basin
Land use, population data	Percent of total area in each of 5 land use groups
Street sweeping frequency and number of passes	Average percent imperviousness of each land use group
Soil erosion data	Runoff coefficients for pervious and impervious areas
Pollutant loading and generation factors	Feet of gutter per acre for each land use group
Sewer layout, shapes, dimensions, slope, roughness	Depression storage available on impervious areas
Specifications of flow control devices	Treatment rate
Infiltration data	Hourly rainfall
Dry weather flows	Daily rate of dust and dirt accumulation per 100 feet of gutter for each land use group
Catch basin data	Pounds of pollutants per 100 pounds of dust and dirt
Treatment and storage facility data	Street sweeping frequency and efficiency.
Tidal variations, water surface elevations and areas, water depths and roughness coefficients for receiving waters	
Receiving water boundary conditions	

Table 3. SWMM and STORM input data [19].

data, it should be verified with a set of data separate from that used in model calibration. Model verification consists of a rational analysis of both the computed output and any empirically derived parameters. Additionally, to provide a proper verification, the computed model output should be compared with observed output (e.g. runoff flows).

Before proceeding with the actual calibration, goodness of fit and accuracy criteria need to be established. A wide variety of such criteria are described in the literature [2]. In urban drainage, criteria for peak flow rates, runoff volumes and times to peak flow are usually sufficient [2].

Several methods of calibration and parameter optimization procedures exist [2]. Complex urban runoff models are typically calibrated by a trial and error procedure. Model parameters are systematically varied until the model output is within the specified range of accuracy as compared against the fixed observed output. The selection of parameters to be calibrated is greatly aided by the sensitivity analysis specifying how model parameters affect the output.

Note that direct model calibration (i.e. in the catchment studied) is not always necessary or possible. In simulations of runoff quantities, calibrated parameters are often transposed from analogous catchments in the same region. A similar procedure may be used for quality simulations, however, with a lesser degree of confidence.

2.2.2 Calibration/Verification Data

Calibration/verification data for urban runoff models generally consist of synchronized observations of rainfall, runoff hydrographs, and runoff pollutographs for a number of events. The following aspects of calibration/verification data are of major interest:

(a) Accuracy of data
(b) Number and type of calibration/verification events.

Accuracy of calibration/verification data

Accuracy of calibration data will affect the calibrated values of model parameters, and consequently, the accuracy of predictions done with the calibrated model. Systematic errors in calibration data may have a dramatic impact on the accuracy of predictions. Random errors are less likely to affect the mean of a set of measurements in a sufficiently large sample. During the period not used for the calibration of model parameters, the errors in the comparison of measured to observed phenomena are likely to be greater than the data errors, because of errors in the fitted parameters. The non-linearity of hydrologic processes precludes theoretical description of the mechanism by which errors in data are transferred to model parameters and then combined with input data errors in the test period to produce errors in the simulated output [16]. A few general considerations can be described.

For flow simulations, random errors in input data such as rainfall are usually compensated for by adjustments in the loss functions (infiltration, detention storage), while random errors in output such as flow are usually compensated for in the routing function [16].

Errors in water-quality simulation are particularly troublesome to define. Principal problems include the high variability of runoff composition and the almost complete lack of knowledge as to processes [16].

Desired accuracies of observed phenomena are specified [16] as follows:

flow data	± 5%
precipitation -	lesser accuracy than flows - probably of the order 10%, avoid systematic errors (undercatch)
Water-quality data	± 25%.

Number and type of calibration events

A manual on Instrumentation and Analysis of Urban Storm Water Data [16] suggests that about 10 - 15 events may be required for model calibration and the same number for model verification. Such a sample would be large enough to reduce the effect of random errors on the fitted parameter values to an acceptable level. While the above numbers may represent an ideal situatión, in urban drainage design, one has frequently to work with a much lesser number of observed events. It should be realized that even a small number of observations of high accuracy will improve model predictions. On the other hand, model calibration against observations of poor accuracy is meaningless. The number of events used for calibration is a compromise between the ideal number (say 15) and the number of events which are available or can be monitored within the time and budget constraints.

Prior to calibration, the calibration data should be thoroughly inspected and obviously erroneous data eliminated. An example of such inspection is computing the ratios of the total runoff to the total rainfall.

Finally, one should realize that not only the number but also the type of events is important. Even a large number of observed minor storms will not yield any information on the maximum infiltration rates if the input of rain water remained well below such rates. Another example is the need to observe storms with various antecedent dry periods in order to assess the pollutant loading rates in the catchment.

2.2.3 Considerations in Calibration of the SWMM Model (Runoff quantity and quality only)

The following example of considerations to be made in calibration of the SWMM model (Runoff Block) was adopted from the SWMM User's

Manual, Version II [18].

Runoff Quantity

Assuming that a careful and thorough evaluation of physical data (such as area, ground slope, percent imperviousness) has been made, the user has flexibility to adjust seven quantity input parameters:

1) Resistance factor for impervious areas
2) Resistance factor for pervious areas
3) Surface storage on impervious areas
4) Surface storage on pervious areas
5) Maximum rate of infiltration
6) Minimum rate of infiltration
7) Decay rate of infiltration.

The first two parameters are likely to affect the timing of hydrographs, the last five parameters will primarily affect runoff values as well as timing. The number of parameters to be adjusted can be further reduced by sensitivity analysis. In the example [18] presented here, the following findings were made for a particular drainage area and a single storm:

The resistance factor for impervious areas had little effect. A 100 fold increase in magnitude resulted in an 18 percent increase in surface storage, but resulted in only a 1.5 percent reduction of the total gutter flow (runoff volume). A 50 fold increase in the resistance factor for pervious areas had no effect. Impervious area surface storage (or detention depth) was more important: increasing its magnitude from 0.001 inch to 0.200 inch resulted in a 100 percent increase in surface storage, and an 18 percent decrease in the total gutter flow. The Model was totally insensitive to a 50 fold increase in the magnitude of the pervious area surface storage parameter. Variation of the maximum rate of infiltration from 1.50 inches per hour to 6.00 inches per hour produced no effects on runoff volume. Variation of the minimum rate of infiltration from 1.50 inches per hour to 0.01 inches per hour (holding the maximum rate and the decay rate constant) resulted in a net decrease of 8 percent in the total volume of infiltration. The runoff volume increased by 75 percent as a result of the decreased infiltration.

The relative effect of the maximum versus minimum infiltration rates is affected by the decay rate. As this rate is increased, the infiltration curve moves rapidly towards its minimum value. As this rate decreases, the infiltration curve remains near its maximum value longer.

The results presented above pertain to a specific drainage basin (41 subcatchments, 134.59 acres) subjected to a specific storm event. Results will vary somewhat depending on the rainfall and the geomorphology of the drainage basin. However, the same parameters should remain sensitive on a relative basis. In summary, the Model is considered sensitive to the following quantity input parameters for calibration purposes:

1) Surface roughness for impervious areas
2) Detention depth for impervious areas
3) Maximum or minimum values of infiltration, the former only for values of the decay rate less than the default value.

Runoff Quality

If the user has measured values that indicate different pollutant loading from those built into the SWMM Model as default values [18], the new loadings can be substituted into the model.

An accurate computation of suspended solids requires erosion data (where applicable). The most significant parameter in the quality simulation is land use classification, since the APWA loading rates are a function of land use types. Other important factors include: (1) the number of dry days preceding the storm event, (2) the street cleaning frequency and number of passes, (3) the volume of water trapped in the catchbasin between storm events, and (4) the BOD (COD) demand exerted by the trapped fluid in the catchbasin.

The number of dry days can be determined from rainfall records and should not be varied for calibration. The volume of trapped water in the catchbasins can usually be determined from sewer plans obtainable from the municipality. In the event of several catchbasin types, an average value may be used. If this estimate is not accurate, this parameter may have to be adjusted during calibration. Few municipalities measure the catchbasin organic demand, thus the user should assume the default value and adjust this parameter according to the results. The street cleaning frequency and number of passes may also be obtained from the municipality.

Neither the catchbasin volume nor the initial concentrations had dramatic effects on runoff quality simulations for a sample run. All catchbasin effects decay as the runoff continues, and disappear entirely after about the first hour of the storm, depending on its magnitude.

2.2.4 Calibration of the STORM Model

Mathematical formulations quantifying the runoff process in the STORM model are much simpler than those in the SWMM model. Consequently, a lesser number of parameters is adjusted in calibration. The brief discussion presented here is limited to the rainfall/runoff computations only since the runoff quality approach in the STORM model is similar to that in the SWMM model which was discussed earlier.

In the STORM model, the runoff quantity is calculated on an hourly basis using the following expression [13].

$$R = C(P - f)$$

where

R = urban area runoff in inches per hour;
C = composite runoff coefficient dependent on urban land use;
P = rainfall plus snowmelt in inches per hour over the urban area; and
f = available urban depression storage in inches per hour.

If observations of precipitation and runoff are available, calibrated values of the composite runoff coefficient C and the depression storage f can be found analytically using e.g. the least squares approximation.

3. Collection of Urban Hydrological Data

Full potential of hydrologic simulation can be realized only if some hydrologic data are available for a city. Note that much of such data is required for any method of analysis and is not pertinent only to hydrologic simulation which is stressed in this presentation.

3.1 Network Design in Urban Hydrology

The collection of urban hydrologic data can be considered as a hydrological network design problem. The objective of such a design is defined here as to specify the number and arrangement of the data-acquisition points which in conjunction with a selected runoff model would yield the minimum error for a given cost, or would indicate where to add observation points to produce the maximum benefit.

The definition of a network for hydrologic data is a matter of some controversy [20]. The following definition [21] was adopted here: "A network is an organized system for the collection of information of a specific kind. Its component parts must be related to one another; that is, each station, point, or region of observation must fill one or more definite niches in either space or time.

A possible classification of hydrological networks appears in Figure 1 [20]. The networks are classified according to their purpose, processes observed, type and frequency of observations, type of field record, length of record, standards of precision, nature of spatial design, and maintenance and quality control. This classification does not bring out differences in levels of intensity of information requirements. Such consideration is made for example in the classification shown in Figure 2 [20]. It is apparent from the latter classification that most of the urban hydrological network fall into level III, i.e. data are gathered for particular operational, legal and administrative purposes concerned with local water resources management. Such networks are rarely subject to design. This statement was also confirmed by the findings of a recent Engineering Foundation Conference which concluded that network design is generally the

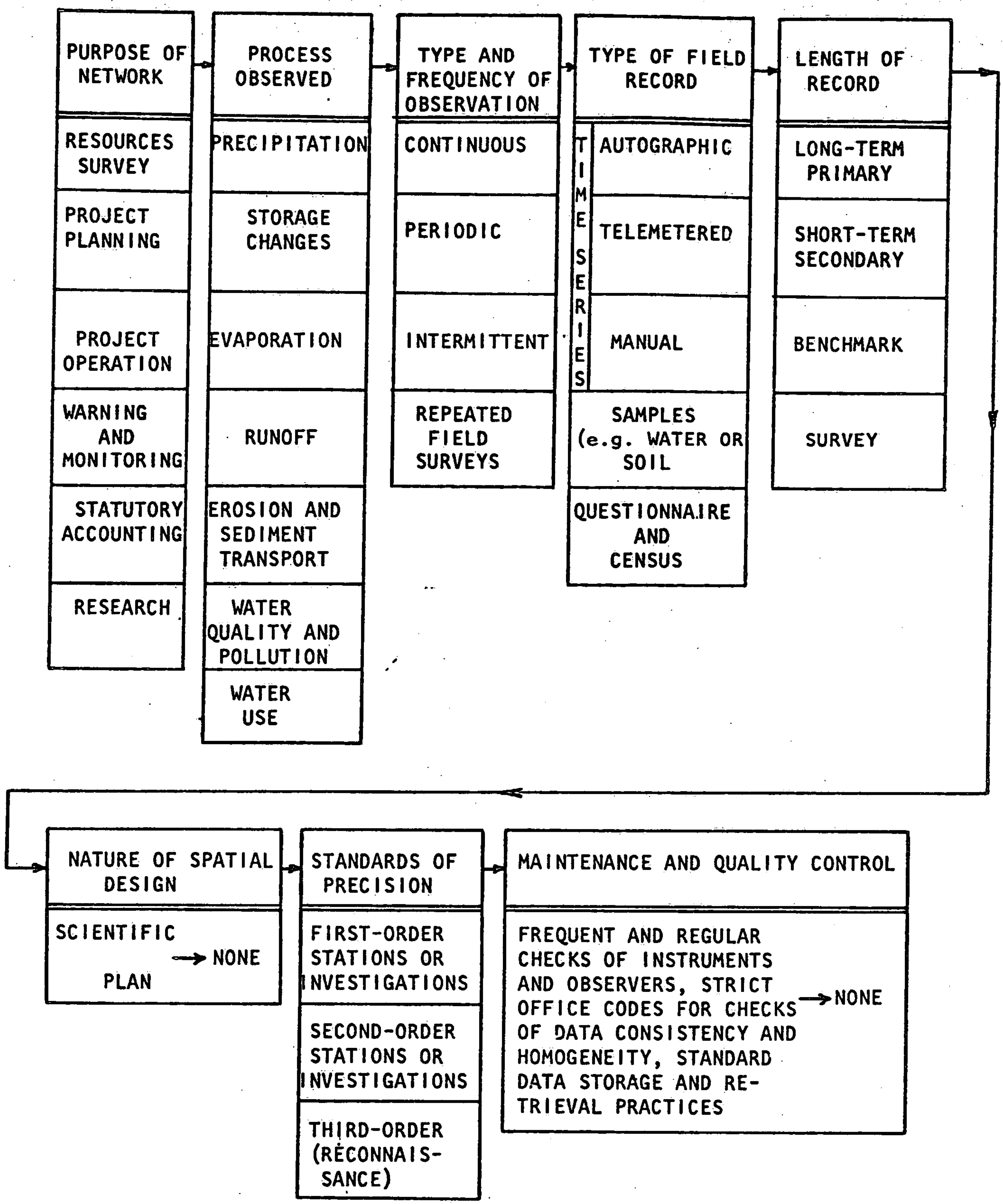

Figure 1. A Suggested Network Classification [20].

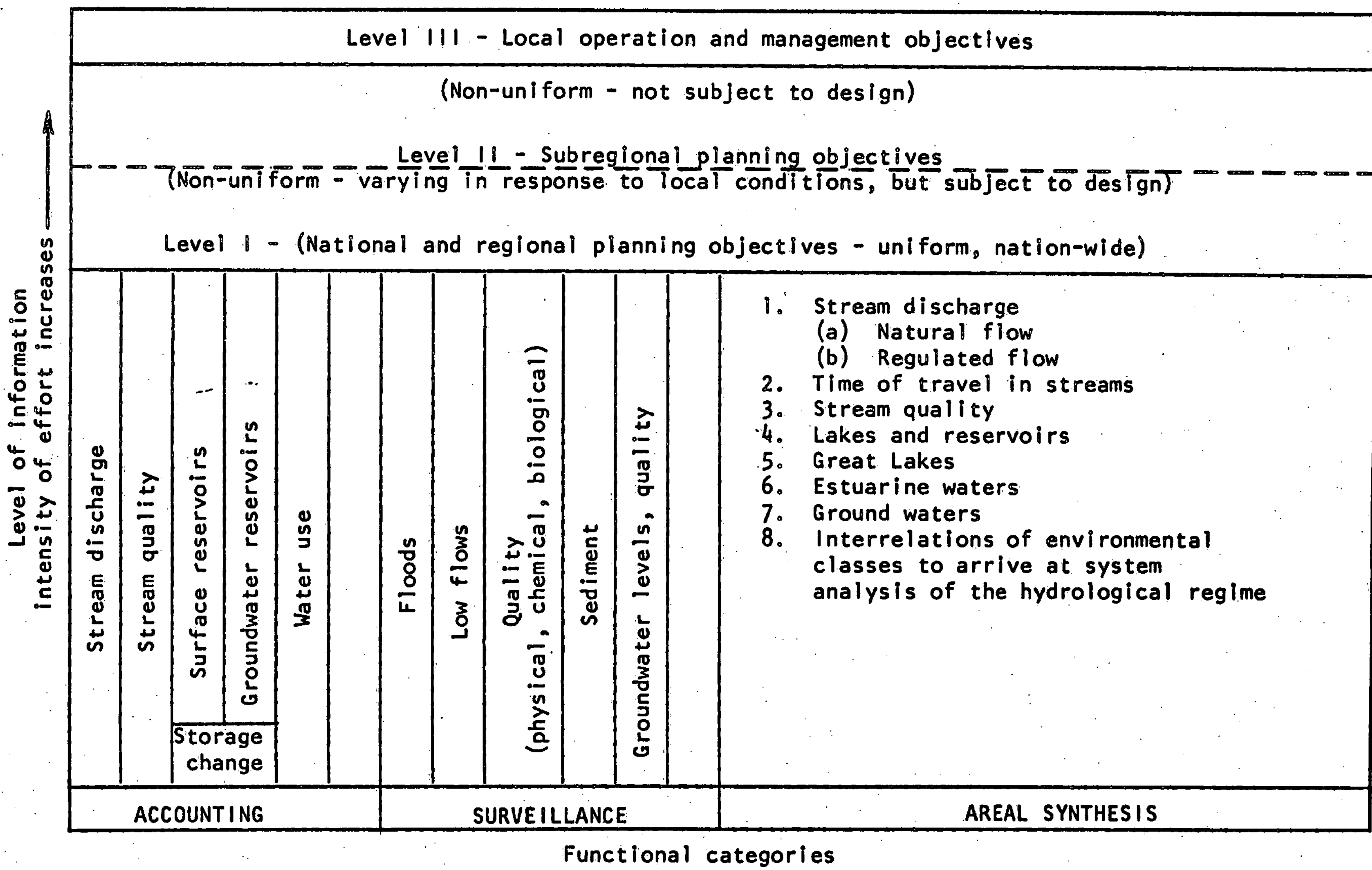

Figure 2. Schematic diagram showing relation of levels of information to functional categories in the U. S. National Water Data Network [20].

most neglected part of urban data acquisition programs [16].

The discussion of urban hydrological networks follows the classification introduced in Figure 1.

Purpose of networks

Among the purposes of urban networks, the most frequent are project planning and design, followed by operation, monitoring and research. The first two items, planning and design are closely related to computer modelling of hydrologic processes. A good example of operational data networks are those employed in the computer-operated combined sewer systems [22].

Typical networks are multipurpose networks. Transferability of data to other catchments within an urban area is of utmost importance.

Processes observed

Most frequently, the following processes are observed: precipitation, runoff quantity and quality, and eventually, changes in storage.

Type and frequency of observations

Precipitation and flows are measured continuously, or intermittently i.e. only during the periods of wet weather. Water quality is monitored periodically.

Type of field record

Most common are autographic records. Water quality is monitored by means of sampling. For large networks or operation of combined sewer networks, data telemetering is employed. The use of recorders producing computer compatible records (magnetic or puched tapes) is economical when large volumes of data are collected.

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Length of record

Typically, short-term secondary records are produced. Depending on the purpose, the data should be collected for the shortest period acceptable. One year, or full seasons of interest are considered as a minimum duration in engineering studies, if the program proceeds successfully [16]. In other cases, the program duration may be dictated by the need to monitor a desired number of calibration/verification events.

Standards of Precision

These standards were briefly discussed in Section 2.2.2. The aforementioned accuracies would correspond to those specified for the first order stations. Lesser accuracies may be fully acceptable in some engineering studies.

Nature of spatial design

Spatial design in urban networks has two facets - firstly the number (density) of data acquisition points, and secondly the location of such points. Scientific spatial design is rarely applied in urban networks, although methodologies for some aspects of such design are available [16]. One such methodology [23] makes it possible to design an optimal rain gauge network in terms of the number and location of stations. The resulting cost and mean square error of estimation are computed.

Other spatial considerations involve selection of the catchments to be monitored within the urban area, and siting and density of instruments.

The effectiveness of hydrologic modelling in the long run will be largely given by the ability of modellers to estimate model parameters on basins which have no data for calibration of the model being applied. Estimation of these parameters can be achieved by transposition of data from the instrumented test catchments. Each monitored catchment should be therefore viewed as a sample of the catchments in the urban area studied. It is imperative that the samples chosen include a set of catchments which are representative of an area's catchment land-uses, types of development, sizes, soil types, hydrologic regimes, etc. [16]. Selection of representative samples is necessary to arrive at a set of transferable model parameters which cover the variations among catchments for the entire urban area.

According to ref. [16], catchment selection begins with an inventory of catchments in the urban area characterizing them at least by size; land use (present and projected); drainage type (fully sewered, degrees of partially sewered, and non-sewered); and relationship to major streams, lakes or estuaries within the area of interest, in terms of sewer outfall and tributary stream entry points, and all previously collected data. For further details, see ref. [16].

The need for multiple rain gauges to characterize the spatial variability of rainfall has been long recognized; however, the need for multiple flow/water-quality monitoring stations to characterize the spatial variability of hydrologic and water quality processes has been virtually ignored [16]. Though recommendations were made to establish a minimum of two flow/water-quality monitoring stations on a catchment [16], such measures may be impractical and costly.

Maintenance and quality control

Maintenance and quality control are often neglected in urban networks. Such neglects together with frequent malfunctions of instruments then result in loss of data. It is not unusual that less than 50% of all the events are successfully and completely monitored. To avoid such loss of data, frequent and regular checks of instruments are recommended together with checks of collected data consistency and homogeneity.

3.2 Instrumentation

Proper instrumentation of catchments is imperative for a good data collection program. Catchment instrumentation includes rain gauges, flow gauges, wastewater samplers and recorders. These instruments and their application in urban hydrological studies were reviewed in several recent reports [4,24,25]. Only a brief discussion of catchment instrumentation follows.

Rain gauges

Precipitation data consists of point precipitation and of the areal distribution of precipitation. Such information can be obtained from a network of several recording rain gauges installed within the studied area. The tipping bucket rain gauge of 0.01-inch (0.25-mm) per tip capacity is particularly suitable for this purpose. A good time resolution, frequently 5-minutes or shorter, is required. Two gauges are sufficient for catchment areas up to 10-km^2 (4-square miles), and for up to 50-km^2 (20-square miles) three gauges are recommended. Time resolutions of rainfall data recommended for urban runoff studies were given in Table 1.

Flow gauges

Runoff flow rates should be recorded continuously at one or more points. Whenever feasible, runoff flows should be measured at the outfall, outside the sewer system. Conventional constriction flowmeters such as weirs or flumes can be used.

If it is necessary to measure inside the sewer system, and the sewer pipe is not frequently surcharged, an inexpensive vertical slot weir or a flume (e.g. Palmer-Bowlus flume) are applicable. For frequently surcharged pipes, a dual free-pressurized flowmeter such as the U. S. Geological Survey Sewer Flowmeter or an acoustic flowmeter should be used.

The acceptable accuracy of runoff flow measurements is 5 to 10%.

Characteristics of selected liquid level sensors and an overview of sewer flow measurement techniques are given in Tables 4 and 5, respectively.

Runoff quality is commonly determined from the laboratory analysis of grab samples collected in the field. Such samples are collected sequentially by automatic samplers. A sampling interval as short as 5 to 10 minutes may be required. The first sample should be collected as closely to the beginning of runoff as practicable. In the currently common approach, a constant sampling interval is selected on the basis of experience and the size of the studied area. A review of ten urban runoff studies (i.e., storm water runoff as well as combined sewer overflows) indicated the sampling intervals shown in Table 6.

Other factors to be considered in the selection of a sampling

Table 4. Characteristics of selected Liquid Level Sensors [4]

Type of Liquid Level Sensor	Application		Typical Installation			Input Power Options (Sensor Only)		
	Free Flow	Pressure Flow	Directly in sewer	In sewer but with some protection	In a stilling well	DC	AC	Other
Capacitance Probe	X	-	-	X	X	X	X	-
Dipper Probe	X	-	X	-	-	X	X	-
Floats	X	-	X (Scow float)	-	X	-	-	none required
Pneumatic Probe	X	X	X	X	-	X	X	X (compressed gas)
Acoustic Probe	X	-	X	-		X	X	-

interval is the precipitation time-distribution and the watershed hydrologic response. These two factors influence the runoff flow rates to which the stormwater quality seems to be related. Consequently, high intensity and low duration summer storms on fast responding watersheds will call for shorter sampling intervals and vice versa.

The first sample should be collected as closely to the beginning of runoff as feasible. This can be achieved by activating the sampler by the first impulse from the precipitation sensor, or better, by the rise of the water level in the sewer by a preselected increment.

Some electronic liquid level sensors (e.g., capacitance probes, Manning Dipper, ultrasonic probes, etc.) can be equipped with alarm relays and these are then used to close the power supply circuit of the sampler when flow reaches the selected level.

The minimum size of samples is about 1000-ml. Great care has to be devoted in order to avoid systematic errors in the sampling. The first step in this direction is to locate the sampler intake at a cross-section where the sampled medium is rather homogeneous. The capability of the sampling apparatus to collect solids should be evaluated, mainly with regard to the intake orientation and the intake nozzle and line velocities.

To reduce the loss of quality data owing to sampler malfunctions, two samplers may have to be installed and operated in parallel.

The selection of water quality parameters investigated in urban runoff studies is affected by a number of considerations. For some

Table 5. Overview of Sewer Flow Measurement Techniques [4]

TECHNIQUE	FREE FLOW	FREE AND PRESSURE FLOW	APPLICABLE AT OUTFALL	APPLICABLE MAN-HOLE	APPLICABLE SEWER PIPE	ESTIMATED ACCURACY	COST RANGE*	RECOM-MENDED
Depth Measurement only	X	X**	X	X		20%	L	No
Depth and point velocity	X		X	X		5%	H	Yes
Specific energy	X			X		20%	L	No
Depth and chord velocity	X	X	X	X	X	3%?	H	Yes
Weirs -								
Rectangular	X		X			5%	L	Yes
V-Notch	X		X			5%	L	Yes
Trapezoidal	X		X	X	X	5%	L	Yes
Vertical slot	X		X	X	X	5%	L	Yes
Flumes -								
Leopold-Lagco	X		X	X		5%	M	Yes
Parshall	X		X			5%	M	Yes
Palmer-Bowlus	X		X	X	X	5%	M	Yes
U.S.G.S.	X	X	X		X	5%	M-H	Yes
Univ. of Illinois	X	X	X		X	5%	M-H	Yes
Tracers	X	X		X		5%	M	No

*: L = Low cost; H = High cost; and M = Medium cost.

**: Measuring pressure drop between two manholes.

Table 6. Sampling Intervals in Urban Runoff Studies [4]

WATERSHED SIZE		SAMPLING INTERVAL	24 SAMPLE CYCLE DURATION
(Acres)	(Ha)	(Minutes)	(Hours)
10	4	5	2
50	20	5-7.5	2-3
100	40	5-10	2-4
500	202	5-15	4-6
1000	455	5-15	4-6
2000	809	15	6
3000	1214	20	8
5000	2023	25-30	10-12

advice in this regard, see ref. [16].

A good time synchronization between the recordings of precipitation, runoff flow and sample collection can best be ensured by recording all this information on the same chart or tape.

3.3 Practical Aspects of Data Collection

Some practical aspects of data collection were dealt with in the preceding section. Additional discussion presented here deals with data analysis and reduction, data storage and management, and costs of collection programs.

Data Analysis and Reduction

The collection and analysis of data should be simultaneous. Delays in data reduction and analysis can reduce the efficiency of the data collection program and result in loss of data. Expedient analysis of data often reveals instrument malfunctions which could remain undetected for long periods of time. Prompt analysis of data may also lead to changes in the data collection procedures.

Data reduction starts with a thorough inspection of all records. The accuracy of data is documented and equipment problems which were recorded in the field book or are apparent from the records are noted. Only data of acceptable accuracy are further processed.

Depending on the type of recorder, rainfall and flow records may have to be digitized.

Analysis of the collected samples requires strict adherence to standard procedures [16]. Water quality of runoff is expressed in constituent concentrations, mass flows and eventually the total mass emitted during an event. The need for good synchronization of sampling and flow records is obvious.

Data Storage and Management

All data should be converted to computer compatible forms (cards or magnetic tapes) for storage. A storage format for Urban Rainfall/ Runoff Data Base was proposed by the University of Florida [26]. Such a format consists of introduction, description of the urbanized area, catchment description, and observed data. Observed data consist of rainfall hyetographs, runoff hydrographs and runoff pollutographs.

Data collected should be plotted at an early stage. A single graph should contain storm hyetograph, hydrograph and water quality data. Such plots are helpful for data inspection and also offer an understanding of catchment response in terms of runoff quantity and quality.

Finally, well-documented and reliable events are selected for further use, such as model calibration and verification.

Costs of Data Collection Programs

The costs of data collection programs vary depending on the purpose and scope of such programs. The costs can be divided into two categories, the initial costs associated with the establishment and instrumentation of the catchment, and operating costs. In the former category, the costs of equipment and its installation are the main items. An instrumentation system consisting of a tipping bucket raingauge, weir, water level sensor, automatic wastewater sampler, and recorder will cost more than $8,000.00. Installations with measuring flumes or a back-up sampler may cost even more, close to $20,000.00.

Operating costs consist of labour costs (site visits and maintenance), sample analyses and costs of supplies.

Site visits are particularly frequent if the collection of water samples is part of the program. Samples have to be collected shortly after the storm and the sampler reset for the next event. The collected samples are then delivered to an analytical laboratory for further processing. The costs of sample analyses depend on the number of parameters studied. The costs of the order of $60.00 to $100.00 per sample are not unusual.

Data collection programs dealing with runoff quantity only are less expensive. The cost of equipment is reduced for the cost of a sampler (about $4,000.00). The analytical costs do not apply and the frequency of site visits can be reduced.

4. Conclusions

Increasing sophistication of urban drainage design calls for application of innovative design tools, such as hydrologic modelling. The full potential of hydrologic modelling can be realized only if sufficient hydrologic data are available for the studied area. Such data consist of various input data and calibration/verification data.

The collection of calibration data consisting of rainfall, runoff quantity and quality, and supporting data, should be considered as a hydrological network problem. The ultimate goal of such collection program should be to produce, in conjunction with an analytical tool (e.g. a hydrological model), urban runoff flows and their composition at any desired point in the urban area. Though the costs of such data collection programs are appreciable, these costs are not excessive in relation to storm drainage costs or benefits derived from improved design.

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